

(19)



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(11)

**EP 0 805 463 B1**

(12)

**EUROPEAN PATENT SPECIFICATION**

(45) Date of publication and mention  
of the grant of the patent:  
**02.08.2000 Bulletin 2000/31**

(51) Int Cl.<sup>7</sup>: **H01B 1/24**, C08K 3/04,  
C08K 7/00

(21) Application number: **97107323.4**

(22) Date of filing: **02.05.1997**

**(54) High thermal conductivity composite and method**

Verbundkörper mit Wärmeleitfähigkeit und Verfahren

Matériau composite à conductivité thermique élevée et méthode

(84) Designated Contracting States:  
**DE FR IT**

(30) Priority: **03.05.1996 US 642469**

(43) Date of publication of application:  
**05.11.1997 Bulletin 1997/45**

(73) Proprietor: **ADVANCED CERAMICS  
CORPORATION**  
Lakewood, Ohio 44107-5026 (US)

(72) Inventors:

- **Marlner, John Thomas**  
Avon Lake, Ohio 44012 (US)
- **Sayir, Haluk**  
Bay Village, Ohio 44140 (US)

(74) Representative: **Geyer, Ulrich F., Dr. Dipl.-Phys.**  
**WAGNER & GEYER,**  
Patentanwälte,  
Gewürzmühlstrasse 5  
80538 München (DE)

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**EP 0 805 463 B1**

**Description**FIELD OF THE INVENTION

[0001] This invention relates to a thermally and electrically conductive composite of thermally treated pyrolytic graphite end/or natural graphite in a polymeric binder which when polymerized under compression forms a solid having high thermal conductivity and low density and to the method for forming a high thermally conductive solid from compressed thermally treated pyrolytic graphite or natural graphite in a polymeric binder.

BACKGROUND OF THE INVENTION

[0002] It is well known that high power electronic assemblies and components are generally provided with an aluminum or copper heat sink for dissipation of waste heat. Similarly, individual integrated circuits are also mounted on aluminum or copper for heat transfer and heat spreading to alleviate hot spots. As electronic device densities continue to increase, more components are packed into smaller areas and management of the waste heat becomes increasingly more important. High temperature can seriously degrade the life of the electronics.

[0003] Hitherto, aluminum or copper has been the material of choice for dissipating and spreading heat. Copper has a thermal conductivity of 380 watts/meter-K which is higher than that of aluminum with a thermal conductivity of 180 watts/meter-K but the density of copper (8.9gm/cm<sup>3</sup>) is over three times that of aluminum (2.7gm/cm<sup>3</sup>). In fact the ratio of thermal conductivity to unit density for copper is 44 as compared to a thermal conductivity ratio for aluminum of 64. Hence, in an application where weight is an important factor aluminum is preferred for use in dissipating heat over that of copper. As electronic items shrink in size, power densities and waste heat become increasing problems and the geometry of the aluminum or copper heat dissipator becomes a limiting factor. For effective heat transfer with aluminum the dissipator will need to be very large whereas for effective heat transfer with copper both weight and geometry considerations prevail. The geometry of the heat dissipator must fit into the space left after the packing of the device is optimized. This necessitates using a dissipator of a versatile formable shape. Materials which have been developed to date as heat dissipating substitutes for copper or aluminum all suffer from low thermal conductivity, high density or rigid geometric design criteria. A low density composite composition comprising flaky graphite and a polymeric binder is taught in U.S. Patent 4,704,231.

SUMMARY OF THE INVENTION

[0004] The material of the present invention is readily formed into any desired shape and broadly comprises a composite of thermally treated graphite or natural graphite comprising particles of graphite in the form of flakes having a hexagonal crystal orientation and an aspect ratio of at least 5 to 1 in a polymeric binder which when polymerized under compression forms a solid having a high thermal conductivity and low density.

[0005] The present invention also comprises a solid composite material consisting essentially of thermally treated graphite particles in the form of flakes having a hexagonal crystal orientation and an aspect ratio of at least 5 to 1 maintained under compression within a polymeric binder with the particles in substantial parallel alignment and with the composite having a thermal conductivity of greater than 100 watts/meter-K and a ratio of thermal conductivity to unit density of at least 50 and up to 200.

[0006] The method of the present invention comprises combining particles of thermally treated graphite flakes or natural graphite flakes having an hexagonal crystal orientation and an aspect ratio of at least 5 to 1 with a polymeric binder to form a composition having at least a 40% graphite particle volume fraction, compressing the composition under a pressure sufficient to substantially align the particles parallel to one another and to the surface of the composition normal to the direction of the applied pressure until said polymeric binder polymerizes into a solid whereby an electrically conductive solid is formed having a thermal conductivity of greater than 100 watts/meter-K.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The advantages of the present invention will become apparent from the following detailed description of the present invention when read in conjunction with the accompanying drawings of which:

FIG 1 is a graph showing the relationship between thermal conductivity and applied pressure upon the composite material of the present invention;

FIGS 2a, 2b and 2c are representative sketches of a cross section of the polymerized composite of the present invention under different loading conditions;

FIG 3 is a photomicrograph at 25x magnification of a test composite of the present invention having a particle

loading of 60% and a thermal conductivity of 114 W/m<sup>2</sup>K at an applied pressure of 9.65 MPa (1400psi); and Fig 4 is another photomicrograph at 25x magnification of a test composite similar to Figure 3 with an identical particle loading and a thermal conductivity of 380 W/m<sup>2</sup>K at an applied pressure of 110 MPa (16000psi).

## DETAILED DESCRIPTION OF THE INVENTION

[0008] Graphite is made up of layer planes of hexagonal arrays or networks of carbon atoms. These layer planes of hexagonal arranged carbon atoms are substantially flat and are oriented so as to be substantially parallel and equidistant to one another. The substantially flat parallel layers of carbon atoms are referred to as basal planes and are linked or bonded together in groups arranged in crystallites. Conventional or electrolytic graphite has a random order to the crystallites. Highly ordered graphite has a high degree of preferred crystallite orientation. Accordingly, graphite may be characterized as laminated structures of carbon having two principal axes, to wit, the "c" axes which is generally identified as the axes or direction perpendicular to the carbon layers and the "a" axes or direction parallel to the carbon layers and transverse to the c axes. Graphite materials which exhibit a high degree of orientation include natural graphite and synthetic or pyrolytic graphite. Natural graphite is commercially available in the form of flakes (platellets) or as a powder. Pyrolytic graphite is produced by the pyrolysis of a carbonaceous gas on a suitable substrate at elevated temperature. Briefly, the pyrolytic deposition process may be carried out in a heated furnace heated to above 1500 °C and up to 2500 °C and at a suitable pressure, wherein a hydrocarbon gas such as methane, natural gas, acetylene etc. is introduced into the heated furnace and is thermally decomposed at the surface of a substrate of suitable composition such as graphite having any desirable shape. The substrate may be removed or separated from the pyrolytic graphite. The pyrolytic graphite may then be further subjected to thermal annealing at high temperatures to form a highly oriented pyrolytic graphite commonly referred to as "HOPG" or "TPG" material. The HOPG or TPG material can be comminuted into a flake like form having a high "aspect ratio" or pulverized into a powder.

[0009] In accordance with the present invention any graphite material is suitable having a high anisotropy such that its thermal conductivity is much higher parallel to the flake surface than throughout its thickness. This includes both natural graphite and thermally annealed pyrolytic graphite inclusive of highly oriented pyrolytic graphite and oriented graphite produced from the pyrolysis of laminated polymeric sheets. It is however critical to the present invention that the selected natural or thermally annealed graphite have a flake like geometry and an "aspect ratio" of at least 5:1. The aspect ratio of the flake refers to its planar dimension relative to its thickness. Stated otherwise, the flake has very little thickness and can, as such, be visualized as a plate like object which is wafer thin having an aspect ratio between its longest planar dimension and its thickness of at least 5:1 and preferably at least 10:1. The planar size of the flake like particles are also important to the present invention in that larger size flakes enhance thermal conductivity. Accordingly the planar dimensions of the flakes e.g. length and width should be as large as practical for reasons which will become clearer in connection with the discussion of FIG 2a to FIG 2c respectively.

[0010] It was discovered in accordance with the present invention that the heat conduction through a composite of high thermal conductivity particles preferably of graphite, when loaded into a matrix of a low thermally conductive polymer resin may be substantially increased by applying a uniformly orienting force normal to the composite surface and maintaining the graphite particles under load as the polymer cures into a solid. Figure 1 is a graph showing the relationship between thermal conductivity and applied pressure as applied normal to the composite surface. The applied pressure causes the graphite particles to align themselves parallel to each other and transverse to the direction of compression. The particles are compressed into an overlapping arrangement as pictorially shown in Figures 2a to 2c with the thermal conductivity of the compressed composite directly related to the magnitude of applied pressure and graphite particle loading. This is readily apparent from the photomicrographs of Figures 3 and 4 showing a cross section of two composite samples (equivalent to the samples in Table 1) of identical highly oriented graphite flake and polymer binder composition at an identical particle loading of 60% but which are polymerized under different applied pressures. Each of the photomicrographs shows the edges of the samples at a 25x magnification. The composite of Figure 3 was formed at an applied pressure of 9.65 MPa (1400psi) and had a thermal conductivity of 114 W/m<sup>2</sup>K whereas the composite of Figure 4 was formed at an applied pressure of 70 MPa (16000 psi) and had a thermal conductivity of 380 W/m<sup>2</sup>K. Particle loading must be greater than 40% to cause an effective increase in thermal conductivity dependent upon the pressure applied. At low particle loadings e.g. ≤ 40% the factor k is independent of orienting pressure whereas at a higher loading, i.e. ≥ 40% factor k is a function of applied pressure. Figure 1 is based upon the data in the following Table 1 derived from a composite sample of highly oriented graphite flake particles loaded into a thermoset epoxy resin system with a volume fraction of 60%:

TABLE 1

Orientation Pressure (MPa)	Thermal Conductivity (W/m <sup>2</sup> K)
3.45 (500 psi)	78

TABLE 1 (continued)

Orientation Pressure (MPa)	Thermal Conductivity (W/m <sup>2</sup> K)
9.65 (1,400 psi)	114
39.30 (5,700 psi)	243
110.32 (16,000 psi)	380

[0011] An additional sample of composite was prepared using natural graphite flake at a 110 MPa (16,000 psi) orienting pressure demonstrating a thermal conductivity of 250 W/mK. The degradation in thermal conductivity using natural graphite as opposed to HPOG or TPG graphite material is likely due to the high ash content of the natural graphite flake used (approximately 12% by weight). The ash, in addition, to being a poor thermal conductor, also impedes particle alignment, particle contact and percolation. From the above data it is obvious that increased orienting pressure would also give an increased thermal conductivity.

[0012] The thermal conductivity of the composite sample was measured parallel to the face of the composite using a conventional laser flash thermal diffusivity test. In accordance with this test the face of a test sample is subjected to a short laser burst and the temperature of the rear face of the sample is recorded. This test sample must be specially prepared to measure the surface thermal conductivity of the bulk composite plates since laser flash measures only through the thickness of the test sample which is perpendicular to the surface direction of concern in the composite. Composite plates were made at various orienting pressures, typically 4mm thick. The plates were cut into 4mm wide strips, each strip rotated 90°, then laminated together to reform a test sample having particle orientation in the test sample in the appropriate direction for the laser flash thermal diffusivity test method. From this measurement and based upon specific heat and upon sample density which is determined from geometry and mass, the thermal conductivity is then calculated.

[0013] For any given applied orienting pressure the higher the particle loading the higher the thermal conductivity up to the point where the composite loses structural integrity. The volume fraction of graphite particles in the composite may extend from 40% to 95% whereas the preferred volume fraction for the graphite particles should be between 55% and 85%. Heat conduction through the composite is a function of percolation. Percolation is the ability of the heat to traverse through the particles in the composite rather than through the polymer matrix. The degree of percolation is controlled by the applied pressure and particle loading and is independent of the composition of the polymer matrix. In fact any polymer composition may be used which will maintain the graphite particles under compression in the polymerized state, preferably a thermosetting polymer such as an epoxy resin. A thermosetting resin is preferred since it will cure under the application of pressure into a solid and remain in the cured state upon release of the applied pressure so as to maintain the graphite particles under compression. This may also be done with a thermoplastic material provided any further working or molding of the thermoplastic material be conducted under load and preferably in a vacuum. The thermal conductivity of the solid composite is established by the pressure applied before it solidifies.

[0014] The composite of highly oriented graphite flakes formed from either HPOG, TPG or natural graphite flakes have a mass density in the range of between 1.6 and 2g/cm<sup>3</sup> which is much less than the density of copper (8.9g/cm<sup>3</sup>) and aluminum (2.7g/cm<sup>3</sup>). Therefore, the ratio of thermal conductivity to mass density for a composite formed in accordance with the present invention is much higher than for Cu or Al.

#### Claims

1. A composite composition comprising particles of highly oriented graphite in the form of flakes having a hexagonal crystal orientation and an aspect ratio of at least 5 to 1 with at least a 40% particle volume fraction of said graphite and a polymeric binder which when polymerized under compression of at least 9.65 MPa (1400 psi) forms a solid having a high thermal conductivity of greater than 100 W/meter-K and a low density of between 1.6 and 2g/cm<sup>3</sup>.
2. A composite as defined in claim 1 wherein said highly oriented graphite comprises thermally treated graphite and natural graphite.
3. A solid composite comprising particles of highly oriented graphite in the form of flakes having a hexagonal crystal orientation and an aspect ratio of at least 5 to 1 with at least a 40% particle volume fraction of graphite substantially uniformly disposed in a polymeric composite having been polymerized under compression into a solid with said graphite particles in a state of compression at a pressure of at least 9.65 MPa (1400psi) and in substantial alignment relative to one another and with said solid composite having a thermal conductivity of greater than 100 watts/meter-K and a ratio of thermal conductivity to unit density of at least 50.

4. A solid composite as defined in claim 3 wherein said highly oriented graphite comprises thermally treated graphite and natural graphite.
5. A method of forming a machinable composite of high thermal conductivity comprising the steps of combining particles of highly oriented graphite flakes having an hexagonal crystal orientation and an aspect ratio of at least 5 to 1 with a polymeric binder to form a composition having at least a 40% graphite particle volume fraction and compressing the composition under a pressure of at least 9.65 MPa (1400 psi) to substantially align the particles parallel to one another and to the surface of the composition normal to the direction of the applied pressure until said binder polymerizes into a solid thereby forming an electrically conductive solid having a high thermal conductivity of greater than 100 watts/meter-K.
6. A method as defined in claim 5 wherein said highly oriented graphite comprises thermally treated graphite and natural graphite,
7. A method as defined in claim 6 wherein said composition is formed having at least a 60% graphite particle volume fraction.
8. A method as defined in claim 7 wherein said applied pressure is above at least 70 MPa (10,000psi).

## Patentansprüche

1. Eine Komposit-Zusammensetzung, die folgendes aufweist:

Teilchen von hochorientiertem Graphit in der Form von Flocken mit einer hexagonalen Kristallorientierung und einem Seitenverhältnis (aspect ratio) von mindestens 5 zu 1 mit mindestens einer 40% Teilchenvolumenfraktion des Graphits und ein Polymer-Bindemittel, welches dann, wenn es unter einem Druck von mindestens 9,65 MPa (1400 psi) polymerisiert wird, einen Festkörper bildet mit einer hohen thermischen Leitfähigkeit von mehr als 100 W/Meter-K und einer geringen Dichte von zwischen 1,6 und 2 g/cm<sup>3</sup>.

2. Komposit nach Anspruch 1, wobei der hochorientierte Graphit thermisch behandelten Graphit und natürlichen Graphit aufweist.

3. Ein festes Komposit, welches folgendes aufweist:

Teilchen aus hochorientiertem Graphit in Form von Flocken mit einer hexagonalen Kristallorientierung und einem Seitenverhältnis von mindestens 5 zu 1 mit mindestens einer 40% Teilchenvolumenfraktion aus Graphit im wesentlichen gleichförmig angeordnet in einem Polymerkomposit, welches unter Druck in einen Festkörper polymerisiert ist, wobei die Graphitteilchen in einem Zustand der Kompression mit einem Druck von mindestens 9,65 MPa (1400 psi) und in wesentlicher Ausrichtung relativ zueinander und mit dem festen Komposit eine thermische Leitfähigkeit von mehr als 100W/Meter-K besitzen und ein Verhältnis der thermischen Leitfähigkeit zur Einheitsdichte von mindestens 50.

4. Festes Komposit nach Anspruch 3, wobei der hochorientierte Graphit thermisch behandelten Graphit und natürlichen Graphit aufweist.

5. Verfahren zum Bilden eines bearbeitbaren Komposits mit hoher thermischer Leitfähigkeit, wobei die folgenden Schritte vorgesehen sind:

Kombinieren von Teilchen von hochorientierten Graphitflocken mit einer hexagonalen Kristallorientierung und einem Seitenverhältnis von mindestens 5 zu 1 mit einem Polymerbindemittel zur Bildung einer Zusammensetzung mit einer mindestens 40% Graphitteilchenvolumenfraktion und Zusammenpressen der Zusammensetzung mit einem Druck von mindestens 9,65 MPa (1400 psi) um die Teilchen im wesentlichen parallel zueinander auszurichten und zur Oberfläche der Zusammensetzung senkrecht zur Richtung des angelegten Drucks bis sich das Bindemittel in einen Festkörper polymerisiert, wodurch ein elektrisch leitender Festkörper gebildet wird mit einer hohen thermischen Leitfähigkeit von mehr als 100 W/Meter-K.

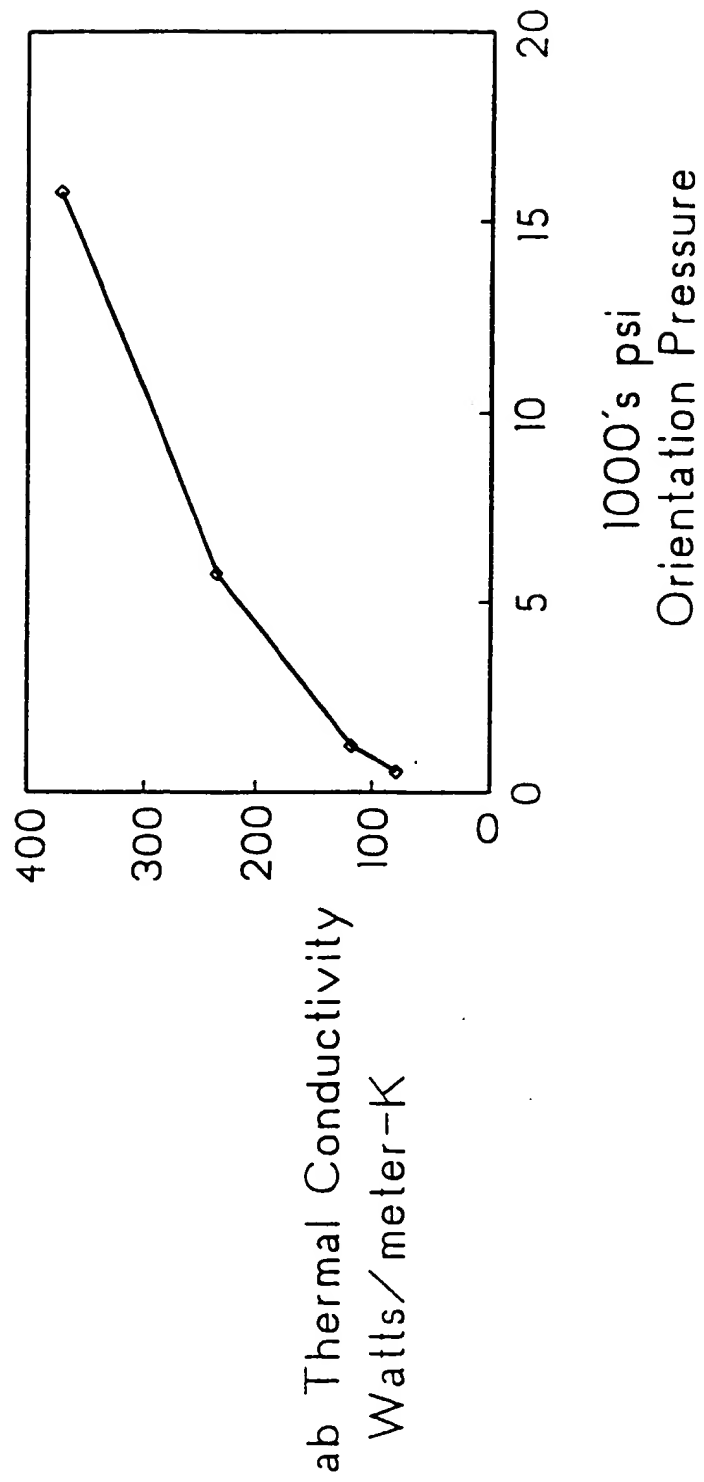
6. Verfahren nach Anspruch 5, wobei das hochorientierte Graphit thermisch behandelten Graphit und natürlichen Graphit aufweist.

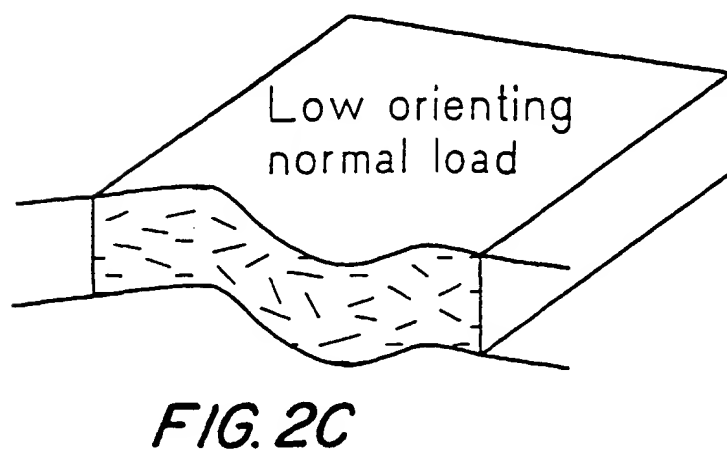
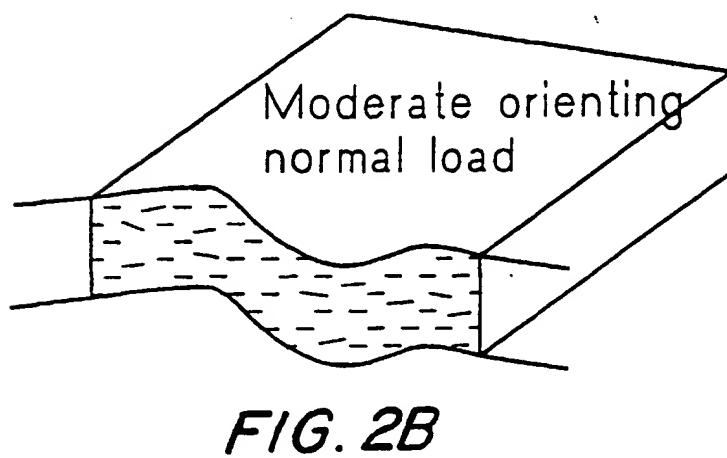
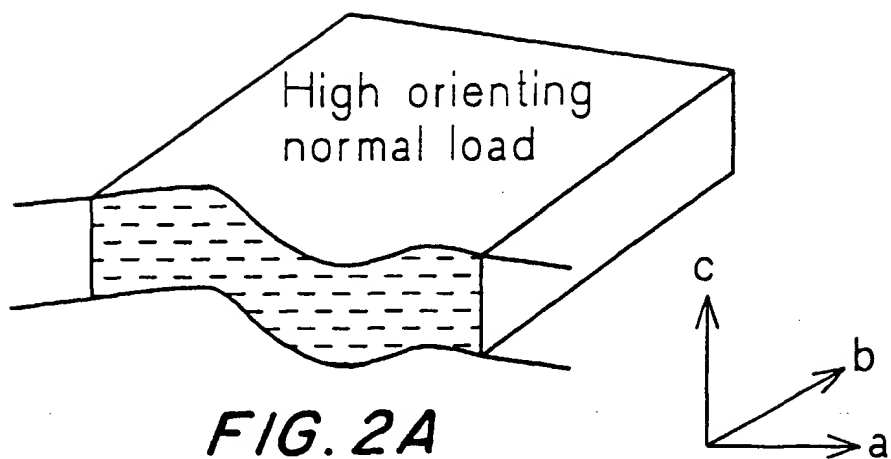
7. Verfahren nach Anspruch 6, wobei die Zusammensetzung mit einer mindestens 60% Graphitteilchenvolumenfraktion gebildet wird.
8. Verfahren nach Anspruch 7, wobei der angelegte Druck oberhalb von mindestens 70 MPa (10000 psi) liegt.

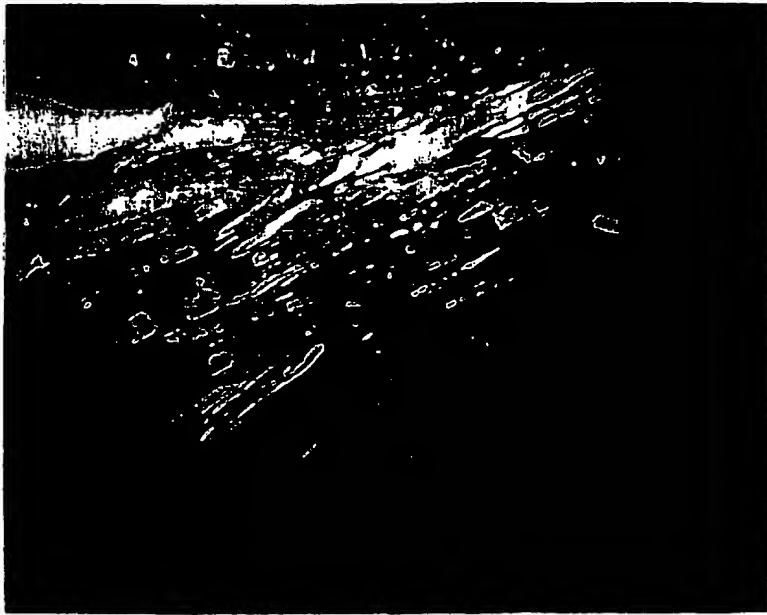
# Revendications

1. Composition composite comprenant des particules de graphite hautement orientées sous la forme d'écailles possédant une orientation des cristaux hexagonale et un rapport d'allongement d'au moins 5 à 1 avec une fraction volumique d'au moins 40% de particules dudit graphite avec un liant polymère qui, une fois polymérisé sous compression d'au moins 9,65 MPa (1400 psi) forme un solide possédant une haute conductivité thermique de plus de 100 W/mètre-K et une faible densité de 1,6 à 2 g/cm<sup>3</sup>.
2. Composite selon la revendication 1, dans lequel ledit graphique hautement orienté comprend du graphite traité thermiquement et du graphite naturel.
3. Composite solide comprenant des particules de graphite hautement orienté sous la forme d'écailles possédant une orientation des cristaux hexagonale et un rapport d'allongement d'au moins 5 à 1 avec une fraction volumique d'au moins 40% de particules de graphite disposées sensiblement uniformément dans un composite polymère ayant été polymérisé sous compression en un solide avec lesdites particules de graphite dans un état de compression à une pression d'au moins 9,65 MPa (1400 psi) et sensiblement alignées les unes avec les autres, ledit composite solide possédant une conductivité thermique de plus de 100 watts/mètre-K et un rapport de conductivité thermique à la densité unitaire d'au moins 50.
4. Composite solide selon la revendication 3, dans lequel ledit graphite hautement orienté comprend du graphite traité thermiquement et du graphite naturel.
5. Méthode de formation d'un composite usinable de haute conductivité thermique comprenant les étapes de combinaison de particules d'écailles de graphite hautement orienté possédant une orientation des cristaux hexagonale et un rapport d'allongement d'au moins 5 à 1 avec un liant polymère pour former une composition comportant une fraction volumique de particules de graphite d'au moins 40% et la compression de la composition sous une pression d'au moins 9,65 MPa (1400 psi) pour aligner sensiblement les particules parallèlement les unes aux autres et à la surface de la composition perpendiculaire à la direction de la pression appliquée jusqu'à ce que ledit liant polymérise en un solide formant ainsi un solide électriquement conducteur possédant une haute conductivité thermique de plus de 100 watts/mètre-K.
6. Méthode selon la revendication 5, dans laquelle ledit graphite hautement orienté comprend du graphite traité thermiquement et du graphite naturel.
7. Méthode selon la revendication 6, dans laquelle ladite composition est formée avec une fraction volumique de particules de graphite d'au moins 60%.
8. Méthode selon la revendication 7, dans laquelle ladite pression appliquée est supérieure à au moins 70 MPa (10 000 psi).

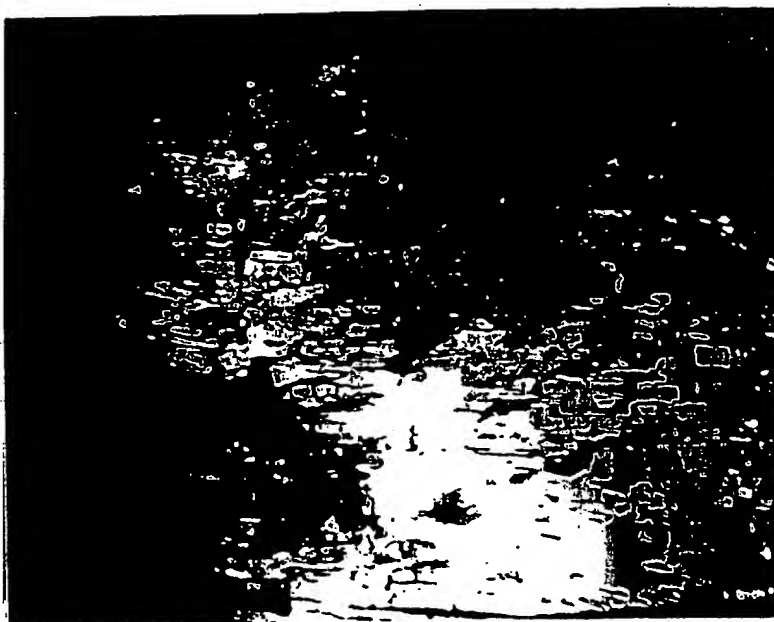
**FIG. 1**







*FIG. 3*



*FIG.4*